CHARACTERIZATION AND COMMERCIALIZATION OF THE COUNTERFLOWING NOZZLE

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Abstract

Interest in the atomization of liquids with different viscosities has been growing tremendously for decades because researchers understood how making an efficient aerosol can improve the efficiency of some applications such as combustion. The process of air-assisted atomization is done by mixing two phase flows, air and liquid. A new atomizer called a counterflowing nozzle was characterized in different conditions in which the low-density outer flow runs counter to the high-density core flow. In this project, both air and water were injected from upstream and mixed before orifice discharge to make a fine mist. Air as an external force is added to the fluid flow and disrupts its attenuated film; therefore, the surface energy increases. While experimenting, water and air flow rate and water and air pressure were changed and the efficiency of spray was observed until finding the optimal conditions. Also, different modes of the nozzle were found. The results of these experiments proved that the flow conditions observed in flow-blurring occurs independent of H/D; therefore, an efficient atomization regime similar to flow-blurring should be observed. Hence, it can create a finer mist compared to other jet-based atomizers. Finally, the marketing plan of the counterflowing nozzle was developed to explain the opportunities that this product has in the market and how it can succeed in industry.

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List of abbreviations:

CF	counterflowing
FB	flow blurring
EA	effervescent atomizer
CAF	core annular flow
ALR	Air liquid ratio
H	distance
D	diameter
m°	mass flow rate
CCM	cubic centimeter per minute
psi	pound-force per square inch
PIV	Particle image velocimetry

Chapter 1: Introduction

Clean combustion requires efficient atomization of liquid fuels. Advances in the efficiency of burning alternative fuels in engines are actively being pursued to revolutionize systems in the transportation and industrial sectors. In 2013, 92% of the 26.9 quadrillion BTUs consumed for transportation came from petroleum, and just under 5% from biomass. In the industrial sector, 40% of the 21.5 quadrillion BTUs consumed was from petroleum and 10% from renewable resources. At these scales even small increases in engine efficiency have enormous impacts on emissions and the production of carbon dioxide [1]. According to a United States Department of Agriculture study, 60% of the energy required to produce biodiesel is attributed to the conversion process [2]. Improving atomization and combustion to the point that bio-oils can be used without damage to gas turbine engines will reduce energy consumption and cost.

Atomization was invented in the 1800s by Dr. DeVilbiss [3], and the interest into this field has been growing tremendously for decades. The process of air-assisted atomization is done by mixing two phase flows, which are air and liquid both air and water were injected from upstream and mixed before orifice discharge to make a fine mist. Air as an external force is added to the fluid flow and disrupts its attenuated film; therefore, the surface energy increases.

Atomization can be achieved through many different jet-based approaches such as airblast (AB) and effervescence (EA), which have been developed. Even though different types of atomizers have been designed, atomization of high viscosity bio-oils still does not occur properly, which leads to deficient combustion. Although AB and EA were an improvement, they could not solve this problem well. Recently, flow blurring (FB) was discovered by Gañán-Calvo in 2005 [4], which increases surface area by 50% at similar air penalties as other airblast nozzles. Even though FB is an efficient atomization method, making an even finer mist, it is hypothesized that the development of absolute instabilities in closed hydrodynamic systems would further improve atomization and therefore combustion. Improved combustion would result in reduced soot production and the release of unburned hydrocarbons.

Therefore, in order to make a very fine mist in a more convenient way for liquids with high viscosity, a counterflowing (CF) nozzle was made for this research, which directs air annularly counter to the core liquid flow. The counterflowing nozzle has a smaller exit diameter due to the interior guiding surface that directs the air up into the liquid stream, hereafter termed ‘counterflow surface’, which leads to a narrower jet issuing from the nozzle. The counterflowing nozzle has advantages over the flow blurring nozzle, such as not requiring a specific geometric condition to be reached before the improved atomization regime is realized. A laser-based diagnostic was used for the experimental approach to quantify the flow and the droplet size within the cylinder and after exiting the end cap orifice.

A marketing plan was developed to successfully commercialize and market the counterflowing nozzle. The marketing plan will help to achieve project goals in an organized way by outlining target markets, market needs, and market trends, creating a SWOT analysis on the product, and finding competitors and their strategies. At the end of the marketing plan, risks, benefits, and keys to success of this new product are explained.

Chapter one is the literature review that covers the history of the nozzle and research that was done in the past by other researchers. It also includes the weaknesses that previous atomizers have. Chapter two discusses the experimental set up and the methodology used and it explains the results taken after each stage of the experiments. The last chapter focuses on the marketing plan and commercialization of the counterflowing nozzle.

1.1 Research objectives:

The major objectives to be addressed in this project are as follows:

1. Characterization of the operating modes of the nozzle
2. Preliminary quantification of droplet sizing for different spray conditions
3. Exploration of commercial uses of the nozzle

Chapter 2: Related Literature and Theoretical Focus

The needs of industries like oil and gas and agriculture to use atomization has been increasing for a long time, which motivated researchers to implement lots of studies to design atomizers and evaluate the behavior of various types of fluids under different conditions. This literature review is organized according to different kinds of atomizers. In addition, for better understanding of the process, spray atomization, spray characterization, and core annular flow are explained based on previous research and books.

2.1 Spray Atomization

First, spray atomization is explained to provide basic knowledge of atomization. A conversion of flow of a liquid into a disintegrated flow with micrometer sized droplets has become important in many industrial processes such as spray coating and spray combustion from years ago. Spray atomization increases the surface energy of a liquid using external forces such as air flow to make small droplets which result in a finer mist [5].

Liquid atomization can be produced using different methods. For instance, ultrasonic vibration which causes instability in the surface of the flow and creates ligaments of liquid and results in droplets. Droplets can also be created using aerodynamic forces and also by using the pressure that is created electrically which is called electrostatic atomization [6].

In the proposed nozzle, atomization occurs by increasing the instability of the liquid and breaking the surface tension of the liquid injecting the compressed air counter to the cylinder by the counterflow surface.

2.2 Spray Characterization

Lefebvre, 1989 [6] stated that consistency in drop size is really important for atomizers' applications. Therefore, characterization and good understanding of the performance of the spray that is affected by variation in the properties of the liquid, operating condition, and the geometry of the nozzle are vital subjects to be addressed before taking any further steps. However, in recent years, laser diagnostic techniques have been used to measure the droplet size and their velocity. In this project, high speed photography was used for starting the characterization of CF atomizer. There are many parameters that can be considered to characterize a spray such as geometry of the nozzle, atomizing gas pressure and flow rate, spray angle, droplet velocity, frequency of the spray, and volume flux.

In this project, the focus on doing experiments and characterization of the nozzle was more on the air and water pressure and their flow rates. Based on the results of the experiments that were done by Xie et al., the spray formation is affected by the ambient pressure and the pressure of injection. These pressures can have major effects on the spray and its efficiency [7].

2.3 Core Annular Flow

Core annular flow (CAF) happens naturally and transports high viscosity liquids such as oil by a liquid with low viscosity such as water. In this process the water will be injected towards the wall of a pipe and the oil that is going to be lubricated by the water will be injected into the pipe at a similar pressure [8]. In other words, flows with disparate viscosity lubricate each other; one of the most famous applications of this phenomenon is pipe-lining.

Lots of research has been done in order to investigate core annular flow. Different types of flow are defined by their stability. Core annular flow is affected by the stability between two flows and a pipe position (vertical and horizontal). Joseph et al., explained the fact that flow condition affects the stability of flow independent of the thickness of flow layers [8]. H. Hu, and Joseph, computed that instability can be best achieved in the "axisymmetric mode of perturbation" with both two layers and three layers of flow [9]. These results were also observed in the water region of a vertical pipe in which two layers were studied by Kim and Choi [10]. In addition, the core-annular flow sets up a mean velocity profile with two inflection points that are highly unstable [10]. They observed that flows with disparate viscosities create waves that have varying wave numbers and amplitudes which make their interface very unstable [10]. Although this instability is detrimental for pipe-lining, the behavior of liquid with very different viscosities that was observed during these studies is a good source for improving atomization. The more turbulent the flow, the better spray can be produced with smaller drop size.

Despite of the CAF that liquids flow in the same direction, in the counterflowing nozzle the low-density outer flow runs counter to the high-density core flow to increase the instability. Co-flowing flowfields have received a lot of attention, including those with highly disparate densities; however, the flowfields described here have not been studied previously.

2.4 Flow Blurring (FB) Atomization

The flow blurring atomizer was designed by Gañán-Calvo in order to create a better mist compared to jet based approaches, which is simpler and inexpensive than them, also. Its configuration consists of a liquid feed tube that is inside a bigger tube that air is injected into. The end cap orifice of the gas feed tube is equal to the liquid feed tube diameter. Gañán-Calvo (2005) used water and ethanol as the liquid fuel for a flow blurring nozzle, so the effect of the viscosity on the spray making is negligible [4]. Flow blurring is theorized to occur through bifurcating the atomizing gas stream so that a portion of the gas stream flows counter to the liquid stream within the nozzle [4]. The best result is achieved at the H/D <0.25 for both ethanol and water where H is the distance between the liquid supply tube exit and the nozzle orifice and D is the diameter of the nozzle orifice [4]. The most salient point of Gañán-Calvo’s article is the range of surface area that produced by flow blurring which is 5 to 50 time greater that other jet based atomizers [4].

Simmons, Panchasara, and Agrawal, (2009) conducted a research study to compare AB nozzle with FB nozzle; water in the airblast atomizer was at ambient pressure and temperature [11]. They found that the FB injector's performance is superior to the AB injector because it makes a spray with a narrower angle that is not dependent on ALRs. In addition to that the spray created by the FB atomizer has a smaller Sauter Mean Diameter and angle [11].

Building on the results of Simmons, Panchasara, and Agrawal, (2009) the goal of this project is to examine the FB nozzle along with a CF nozzle. The CF nozzle is developed to set up a counterflowing core-annular flowfield without the requirement of a specific geometric condition being reached, as is needed in the FB nozzle [4].

2.5 Effervescent Atomizer

Effervescence atomization was developed by Lefebvre and his colleague in 1980 [12], and it was recognized formally after being published by Buckner and his co-workers in 1990 [13]. Unlike air-blast and flow blurring, an effervescent atomizer is an internal twin fluid atomizer. The configuration of an effervescent atomizer is such that gas is injected at a very high pressure in order to make bubbles in the water which is injected to the same tube with the lower pressure than the gas. The low velocity of the injected gas not only helps to make much better bubbles at the upstream of discharge orifice but also increases the efficiency of the fuel, which reduces the cost compared to other conventional two-phase flow atomizers [12, 14].

Bubbles are made by two phenomena. In the first one, which was investigated by Roesler and Lefebvre, the bubbly flow upon leaving the exit orifice experiences a quick drop in environmental pressure. The pressure difference disintegrates the liquid into small droplets [12, 15]. In the second one, which was examined by Buckner and Sojka, annular flow occurs within the exit orifice. The rapidly expanded gas core makes very thin ligaments and subsequently atomization occurs because of the aerodynamic phenomenon [12, 16].

2.6 Airblast Atomizer

In an airblast atomizer, the high pressure injected air causes water droplets to form from the injected liquid sheet with high velocity. Four different types of airblast atomizers have been designed in order to create a better spray for different applications; these are piloted, airblast simplex (ABS), pre-filming and plain jet airblast atomizers [17].

The piloted atomizer was designed in order to overcome problems of the original airblast atomizer which is not able to make effective spray at engine start up because of low air velocities [17].

In the ABS air is injected to the nozzle repeatedly and liquid of all kinds can be supplied to the nozzle in different conditions without any limitation. Although the ABS has advantages over the pre-filming atomizer, it collapses at the certain ambient pressure and very specific conditions are required in order to fix this drawback in the nozzle [17]. Compared to other air blast atomizer, the plain jet has the simplest configuration. Although it doesn't have many applications, this type of airblast atomizer can create the mean drop size out of fuels that other types of air-blast nozzle are not capable of [18].

Since plain jet proved to have a better performance compared to other airblast atomizers, in this study the counterflowing nozzle focuses on eliminating weaknesses of the latest plain jet atomizer design.

2.7 Summary

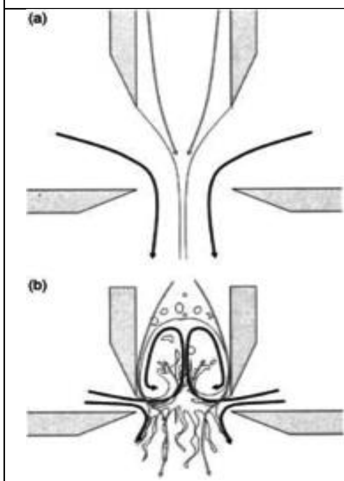
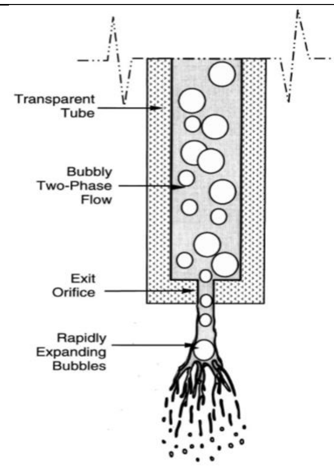
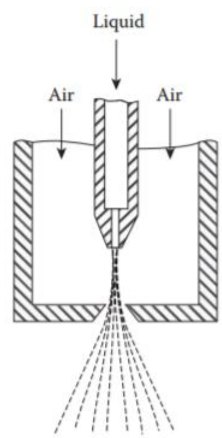
The counterflowing nozzle improves upon the previously designed nozzles, illustrated in table 1, by eliminating their weaknesses. Although Gañán-Calvo revolutionized atomization phenomenon, the patented counterflowing nozzle has advantages over the flow blurring nozzle, such as not requiring a specific geometric condition to be reached before the improved atomization regime is realized. However, the flow blurring nozzle is important to consider because of its similar flow features.

Although EA could make finer mist as a twin-fluid atomizer, the high pressure used for injecting the bubbled gas is not an easy process, so it cannot have many applications. Moreover, compared to the external mixing atomizer, it is more expensive and harder to make.

Even though the effervescent atomizer experiments were done using high pressure gas, stability in droplet size and droplet distribution in the spray cannot be obtained because of the low velocity of the liquid and the sudden drop in pressure after it exits the orifice. Therefore, in order to avoid the same problems as EA, counterflowing nozzle was designed, which can make fine mist using reliable air pressure.

The main drawback of the airblast atomizer design is that atomization performance degrades as lower gas velocities are used because the mechanism which induces liquid instabilities necessary for droplet formation is the air pressure energy. In other words, a steady supply of relatively high speed air is required for proper performance of airblast atomizers.

Table 1: Different types of jet-based nozzles [4, 14, 17].

Flow Blurring atomizer	Effervescent atomizer	Plain jet atomizer
		

Chapter 3: Methodology

3.1 Introduction

After explaining the design of the counterflowing nozzle and experimental setup schematic, a discussion of the characterization of the nozzle is presented in three sections.

Section 3.3: Optimal geometric conditions

Section 3.4: Different frequency modes

Section 3.5: Discussion

3.2 Counterflowing nozzle

The counterflowing nozzle was developed to set up a counterflowing core-annular flowfield, similar to Figure 1, without the requirement of a specific geometric condition being reached, as is needed in the flow blurring nozzle.

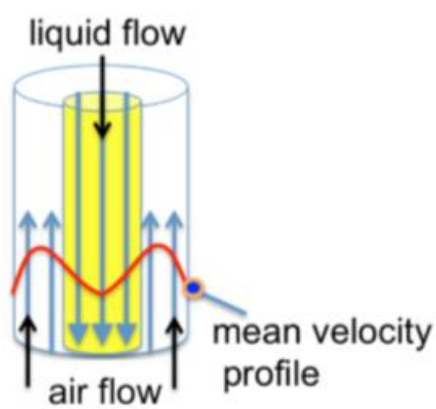


Figure 1: Counterflowing core-annular gas/liquid flowfield.

The counterflowing nozzle, as shown in Figure 1, directs air annularly counter to the core liquid flow. Preliminary geometries developing both flowfields were built out of clear plastic to provide an initial visualization of the two-atomization regimes. Mean images of counterflowing nozzle are shown in Figure 2. The counterflowing nozzle has a smaller exit diameter due to the interior guiding surface that directs the air up into the liquid stream, hereafter termed 'counterflow surface.' The smaller exit diameter leads to a narrower jet issuing from the nozzle. The airflow bubbles up into the liquid tube a small distance, as presented in Figure 2.

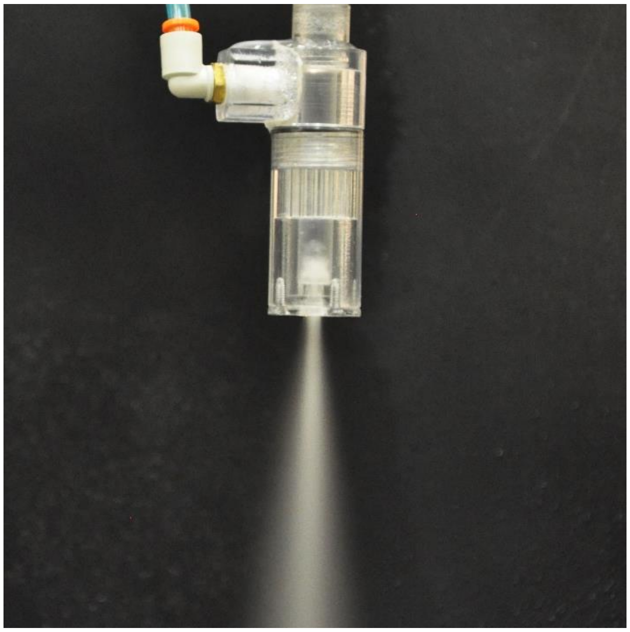
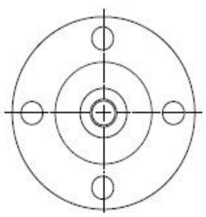
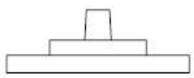


Figure 2: Mean image of counterflowing nozzle.

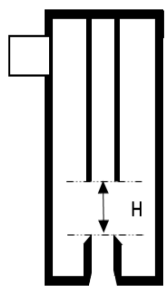
The end cap of the counterflowing nozzle that has the feature of counterflow surface is displayed schematically in Figure 3 (a, b).



a.



b.



c.

Figure 3: Top (a) and front (b) view of counterflowing nozzle endcap (c) distance (H).

In this study, the atomizing air was supplied to the nozzle from the top vent. Next, water was injected into the nozzle with a tube. This mixture of air and water precipitated the counterflowing phenomenon, by which air flowed inside of the tube before water was exhausted from the tube (Fig. 4). The water tube can be moved vertically from the tip of the counterflow surface in order to create the fine spray. The tube inside diameter, d, was fixed at 1.56 mm. The water tube was manipulated manually to find the optimal distance from the tube tip to counterflow surface, H (Fig. 3.c). Figure 4 illustrates the inner path for the counterflow atomization under these conditions in the nozzle.

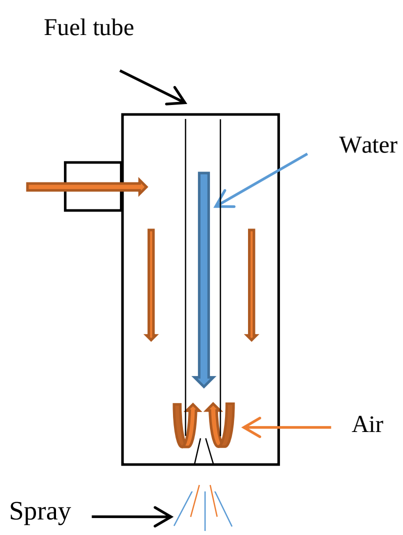


Figure 4: Counterflow Atomization inner path.

Figure 5 depicts the schematic graph of the experimental setup. The water was supplied through the water pressure regulator to control the flow pressure and then passed into the ball valve. The ball valve allowed the experiment to be stopped in an emergency situation. After leaving the ball valve, water entered the flow meter, and next the pressure gauge, before entering the nozzle. At the same time, compressed air was delivered to the pressure gauge, and then passed through the flow meter. The air was entered to the nozzle from the top vent. A bucket was situated downstream of the spray to collect the water.

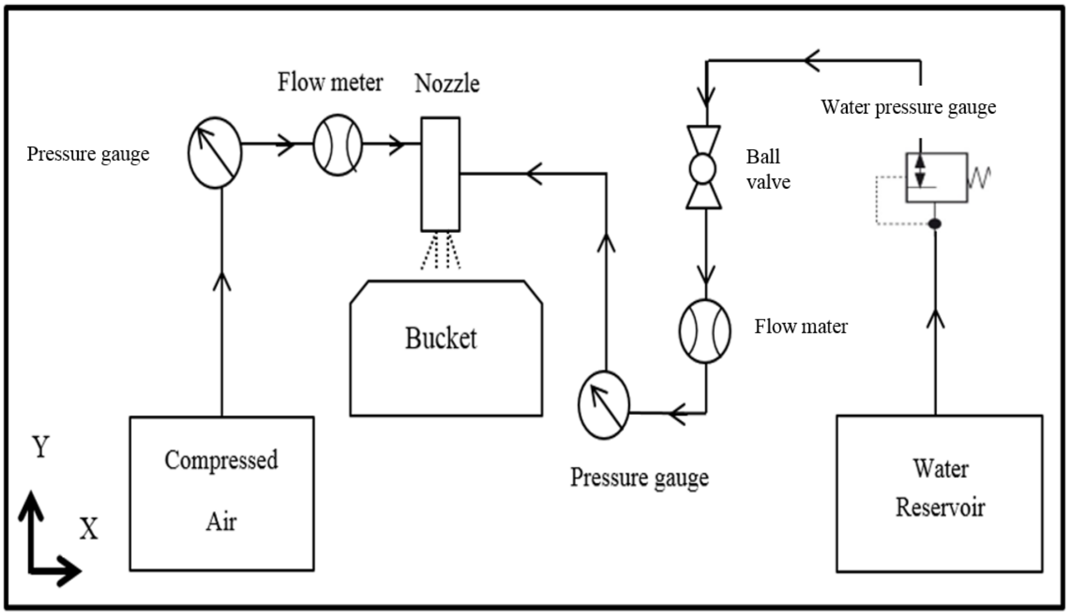


Figure 5: Experiment setup schematic.

3.3 Optimal Geometric Conditions

3.3.1 Finding relation between different parameters (angle of the spray, ALRs, pressure and flow rate of air and water)

To do the experiment, the liquid tube was adjusted at different distances from the end cap for an H<1.5207 mm, or higher than this, the air flow could not penetrate the water tube properly. As can be seen in table 2, at each distance, the water pressure was measured by increasing the air pressure from 10 to 50 psi, while the water and air flow rate were kept constant at 10 CCM. For the next experiment, the water flow rate was increased at intervals of 10 CCM while the air pressure was increased from 10 to 50 psi. After that, the air flow rate was increased from 10 to 20 CCM, and the previous experiments were repeated.

Finally, the water pressure was measured by increasing the air pressure and air flow rate until changes could no longer be made by increasing the air pressure. The final experiment was done at the length of -0.479 mm; distances less than this prevent air from flowing counter to water flow into the tube.

The length was measured by Vernier Caliper. The origin for this measurement was the tip of the counterflow surface. A positive number showed that the exit of the water tube was farther from the tip of the counterflow surface and a negative number showed that the water tube covered the counterflow surface.

3.3.2 Relation between angles and air liquid ratio (ALRs)

In this step, angles of spray as they left the nozzle orifice were measured at different air liquid ratios (ALRs). Air liquid ratios were found using equation 1:

$$ALRs = \frac{m^{\circ}\,(air)}{m^{\circ}\,(water)} = \frac{air\ mass\ flow\ rate}{water\ mass\ flow\ rate} \qquad \text{Eq. 1}$$

The air pressure and air flow rate were kept constant. The water flow rate was increased at intervals of 10 CCM and the air pressure was increased from 10 to 50 psi. Figure 6 shows different spray angles at air pressure of 10 psi. Figure 7 shows the results of all experiments that were done in this step.

Table 2: Measured angles of the spray in different ALRs.

kg/min	**kg/min**			**psi**	**psi**
m (air)	**m(water)**	**Ratio**	**Angle**	**P(Water)**	**p(air)**
0.00001184	0.01	0.001184	3.3	5	10
0.00001184	0.02	0.000592	6	9	10
0.00001184	0.03	0.000395	7.5	10	10

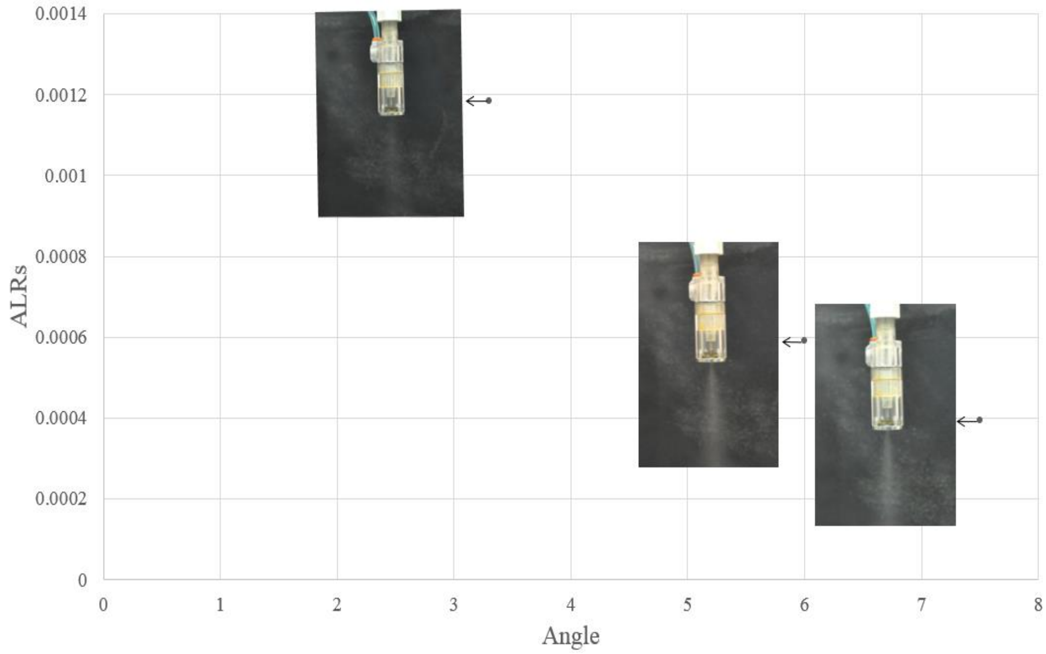


Figure 6: Angles of the spray at air pressure of 10 psi.

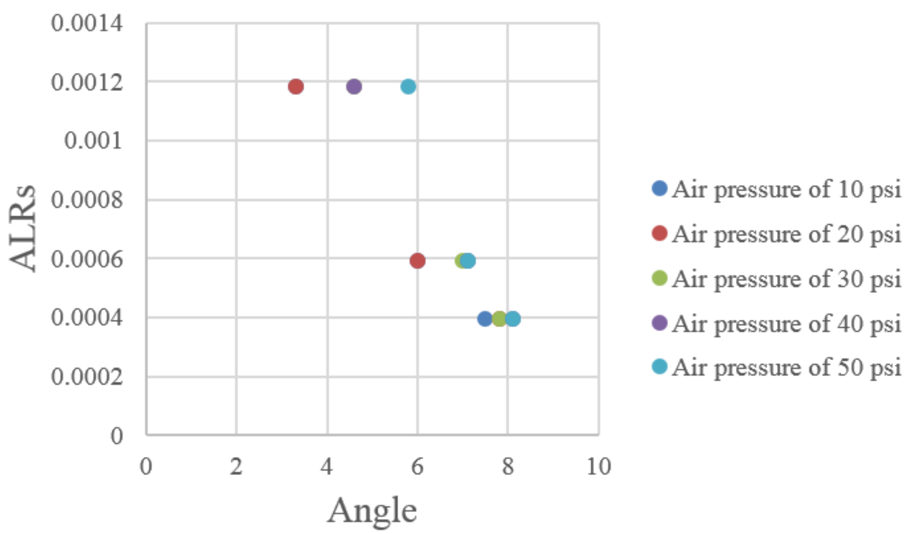


Figure 7: Measured angles in different ALRs at pressure of 10, 20, 30, 40, and 50 psi.

As shown in Figures 6,7, the angles slightly change from 3.3 to 8.1 degree by decreasing the ALRs at the constant air flow rate of 10 CCM. More importantly, observation showed that the optimal spray can be achieved at the water flow rate of approximately 10 to 15 CCM and air pressure of 50 to 60 psi.

3.3.3 Behavior of the air flow rate at different H.

When the air flow rate and water flow rate were held constant, it was observed that the air flow rate was proportional to the distance between the water tube exit and the end cap orifice. Figure 8 shows the behavior of the air flow rate at different distances. The air flow rate and water flow rate were not changed manually.

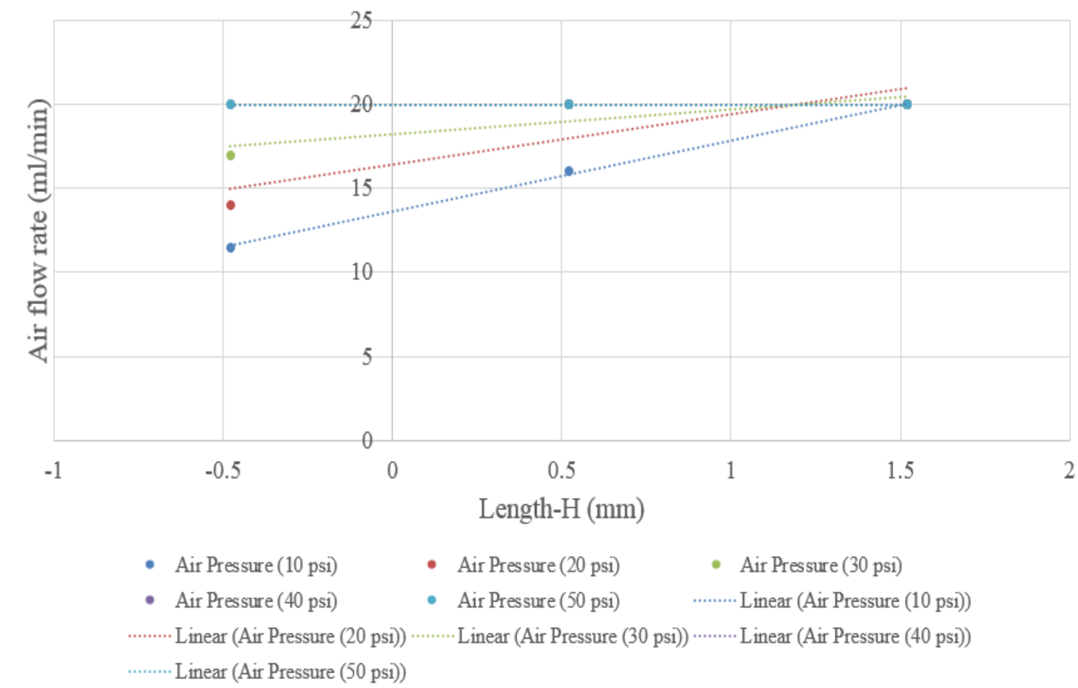


Figure 8: Air flow rate at different lengths.

Based on the results, in order to have more efficient counterflow, the water tube exit should be as close to the tip of counterflow surface as possible. The fine mist was found at a distance of 0.5207<H<1.5207. The zero distance was when the water tube was touching the tip of counterflow surface, negative distance was when the water tube covers the counter flow surface, and positive distance was when the water tube was not touching the counterflow surface. The main advantage of the nozzle is creating countercurrent flow spontaneously, therefore H does not have to be fixed at specific point and it can vary between 0.5207 to 1.5207 mm.

3.3.4 Behavior of air flow rate at different water pressure

In this stage the water flow rate was kept constant and air pressure was increased by intervals of 10 psi. Air flow rate was investigated instead of being changed manually. Lastly, it could be seen that the water pressure increased at constant water flow rate by increasing the air pressure. Air flow rate increased also. As illustrated in figure 9, higher water pressure added to higher flow rate contributed to having more turbulence and unstable flow in the water tube that resulted in a better mist. The best spray was found at the air pressure of 50 psi and air flow rate between 9 to 12 CCM. These results agreed with findings taken from the first step of the experiment.

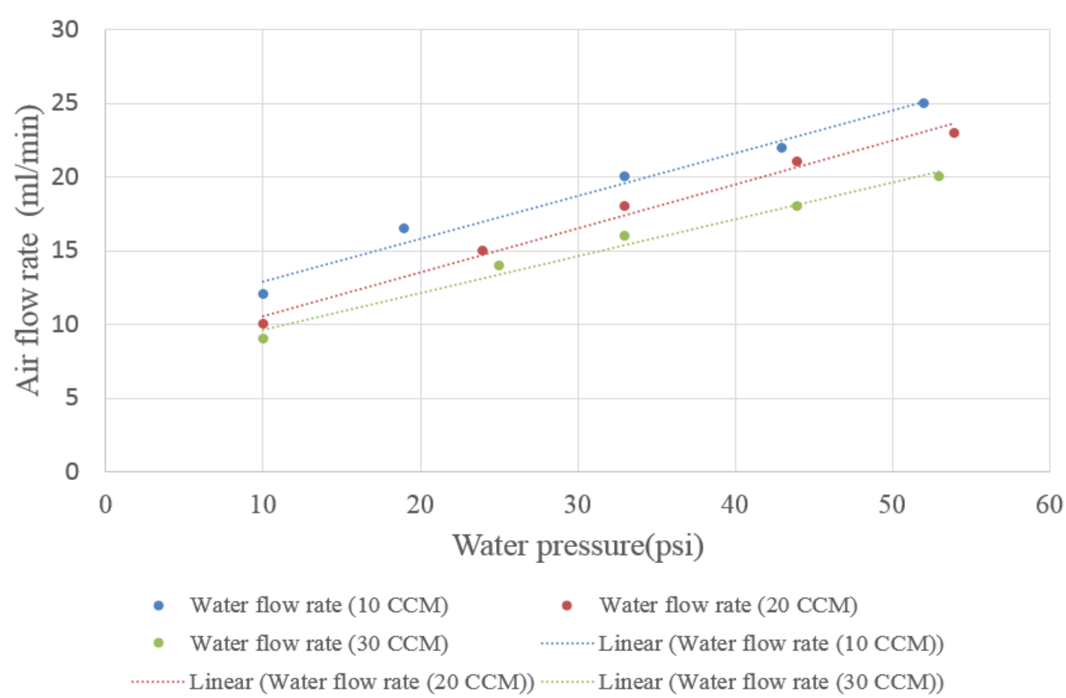


Figure 9: Air flow rate at different water pressure.

3.3.5 Relation between air flow rate and water flow rate

In this experiment the air pressure was kept constant and water pressure was held similar to air pressure. The water flow rate was changed at intervals of 10 CCM while the air flow rate was kept at the highest possible CCM. The air flow rate was plotted versus water flow rate (Fig.10). The air flow rate decreases by increasing the water flow rate at constant air pressure and similar water pressure. Thus, water flow rate affected air flow rate negatively which decreased instability in the flow.

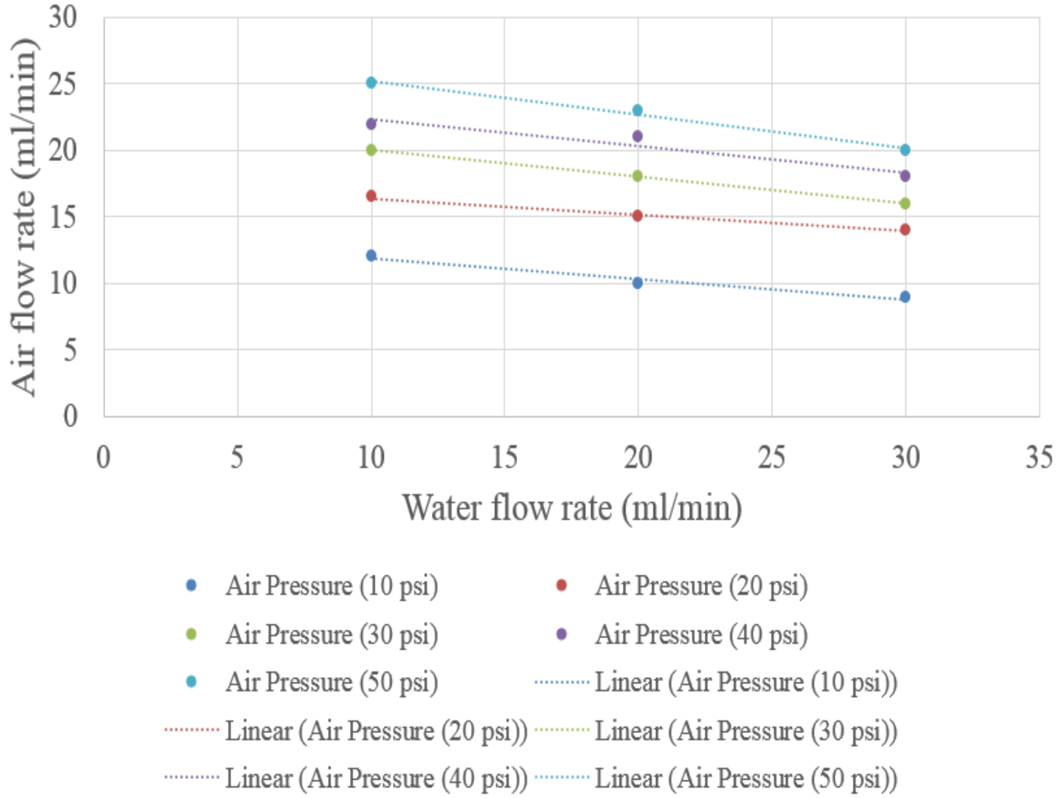


Figure 10: Air flow rate at different water flow rate.

3.4 Different Frequency Modes

3.4.1 Frequency

An interesting behavior was observed when H was 0.5, 0.4, 0.3 and 0.21 mm. The flow began to pulse at a consistent rate which is desirable because it increases the number of applications of the counterflowing atomizer. This section describes this unique flow regime.

With this in mind, a pump was added where water injected into the system for better control of water pressure. Experiments were repeated at pump pressures of 50, 60 and 70 psi. The water tube distance from the counterflow surface was changed vertically until finding a place that water started pulsing. Water pulsing occurred when H was 0.5, 0.4, 0.3 and 0.21 mm. Distances less than those four points created continuous spray and distances more than those four did not result in anything except air flow or accumulated water in the nozzle.

First, frequency was measured in the water flow rates of 10 and 20 CCM and air pressures of 20, 30 and 40 psi with a pump pressure of 50 psi. Then, the frequency was investigated in the water flow rate at intervals of 5 from 10 to 25 CCM at air pressures of 30, 40 and 50 psi with a pump pressure of 60 psi. Finally, frequencies were measured in the water flow rate at intervals of 5 from 10 to 25 CCM and air pressures of 50, 60 and 70 psi at a pump pressure of 70 psi. In all of these conditions, the air flow rate was observed and was not changed manually. These processes were done at the different lengths mentioned previously. Figures 11 to 20 shown in the sections below describe relations between different parameters.

3.4.2 Frequency vs. water flow rate at different air pressure

In order to understand how frequency changes at different water flow rates (10 and 20 CCM) and air pressures (20,30, and 40 psi), frequency was plotted versus water flow rate. The pump pressure was increased by an interval of 10 from 50 psi to 70 psi. At the pump pressure of 60 and 70 psi, the frequency was measured at water flow rates of 10, 15, 20 and 25 CCM. Also at the pump pressure of 60 psi, the air pressure was increased by an interval of 10 from 30 to 50 psi and at the pump pressure of 70 the air pressure increased by an interval of 10 from 30 to 60 psi.

Measurements were taken at these distances (H), 0.5, 0.4 and 0.3 mm. Figures 11 to 13 show that frequency is increased by increasing the water flow rate which is a positive outcome. Different colors illustrate air pressures.

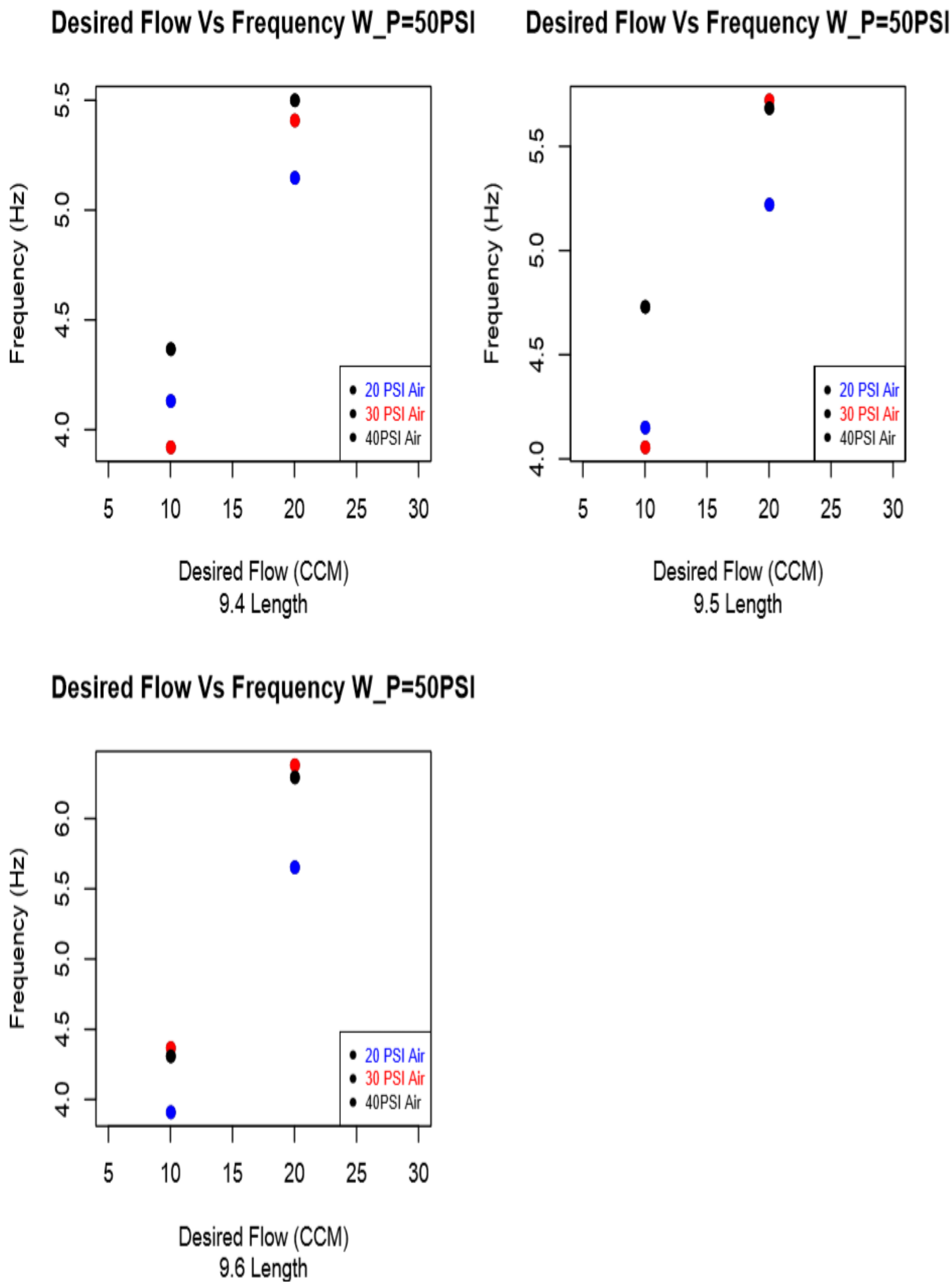


Figure 11: Frequency vs. water flow rate at different distances at air pressure of 50 psi.

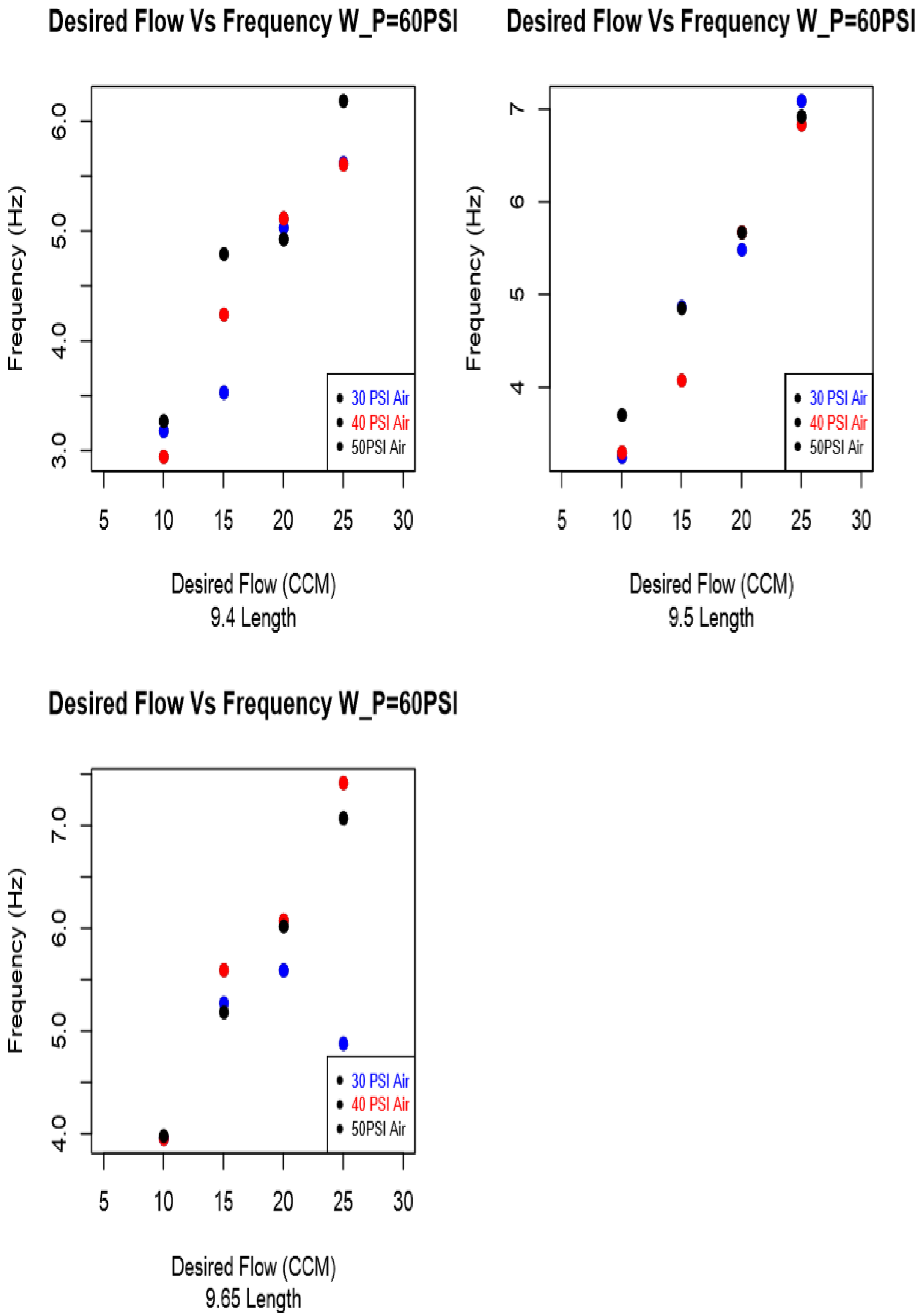


Figure 12: Frequency vs. water flow rate at different distances at air pressure of 60 psi.

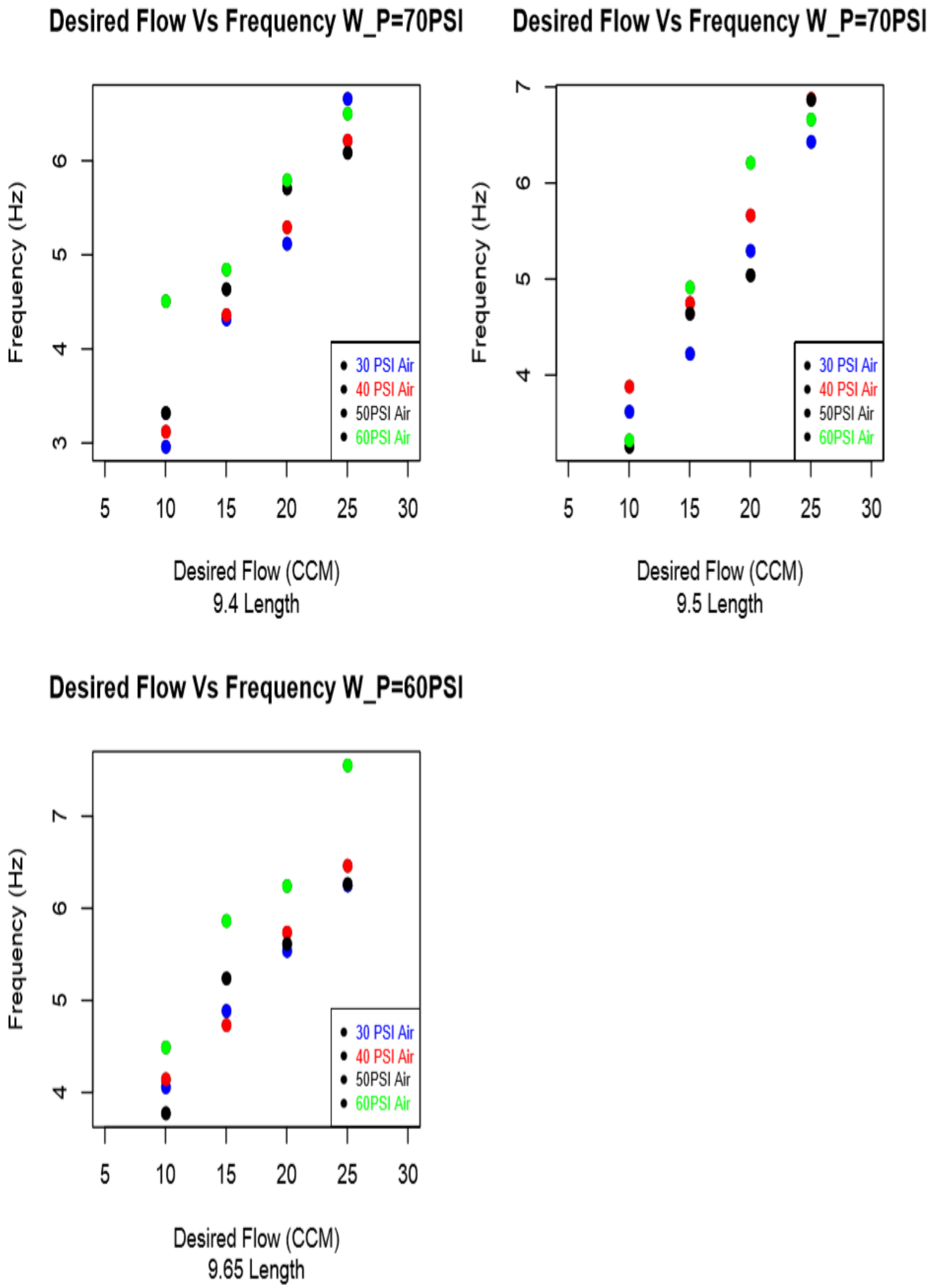


Figure 13: Frequency vs. water flow rate at different distances at air pressure of 70 psi.

3.4.3 Frequency vs. water flow rate at different water pressures

Previously, it was observed that water flow rate can strongly affect atomization. Therefore, under the circumstances described in sections 3.4.1 and 3.4.2, frequency was plotted versus water flow rates and colors represent different water pressures, as illustrated in figure 14 to 16. This was done at lengths of 0.5, 0.4 and 0.21 mm. Figures depict that frequency is increasing by increasing the water flow rate and water pressure.

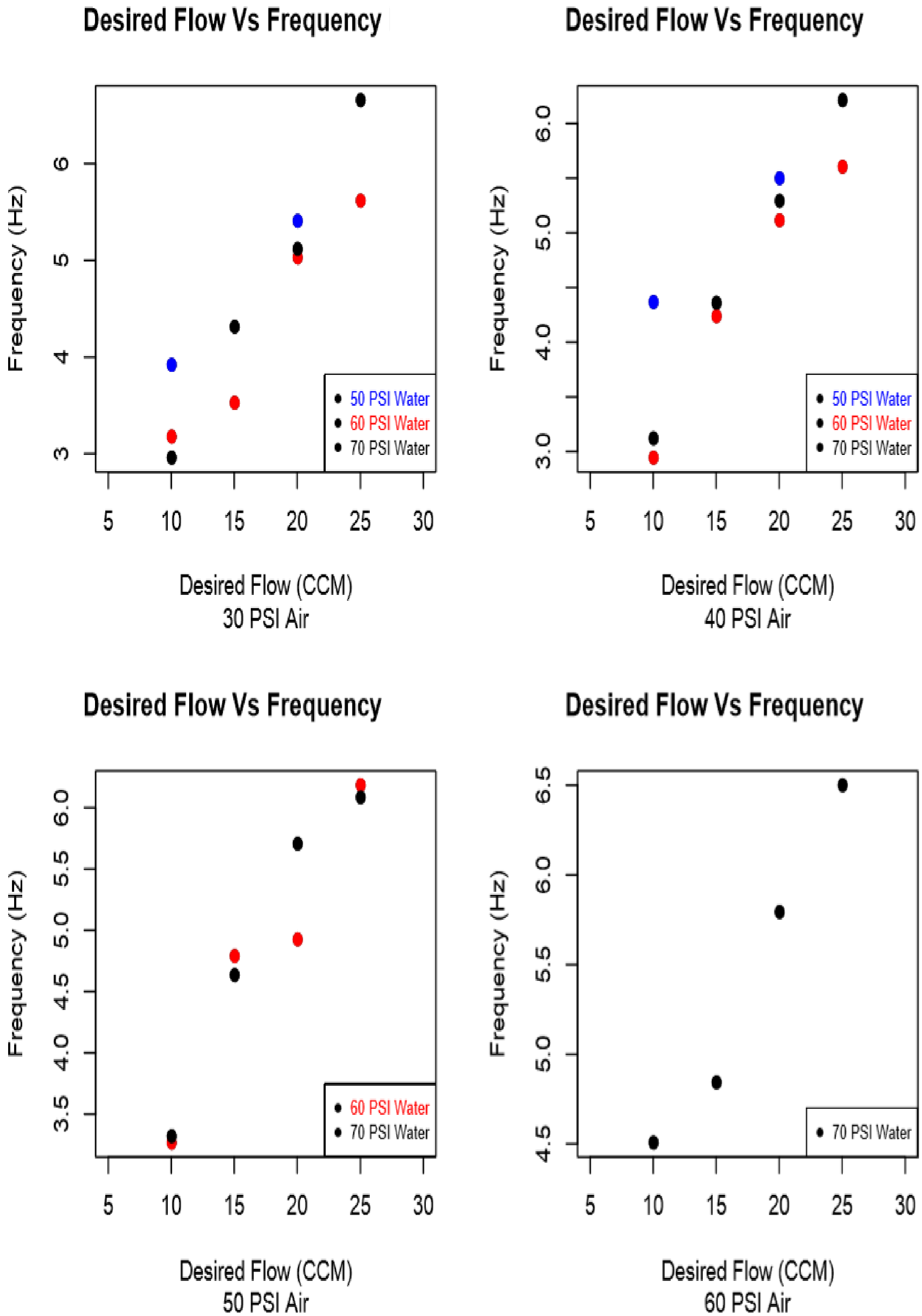


Figure 14: Frequency vs. water flow rate at different water and air pressure at the distance of 0.5 mm.

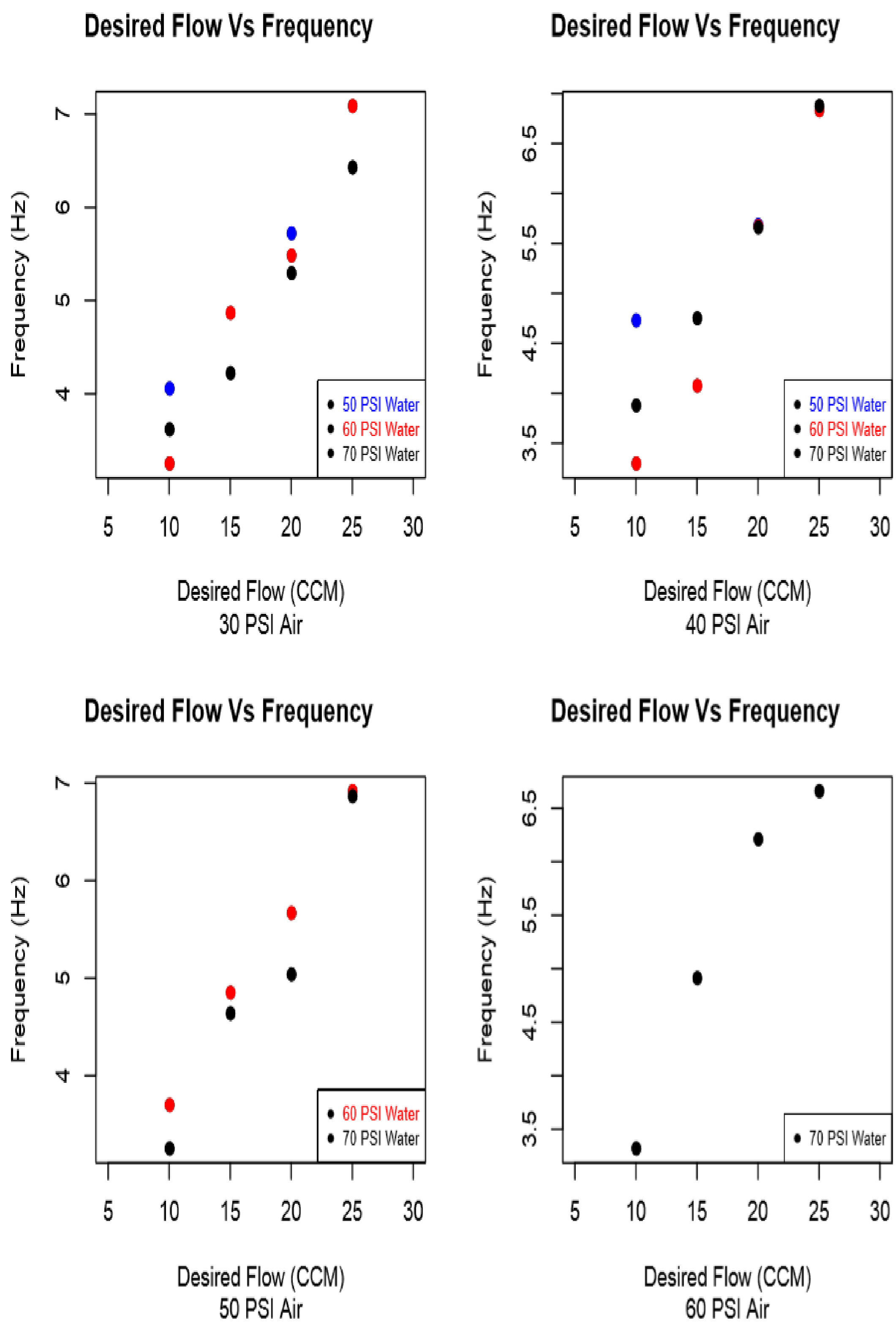


Figure 15: Frequency vs. water flow rate at different water and air pressure at the distance of 0.4 mm.

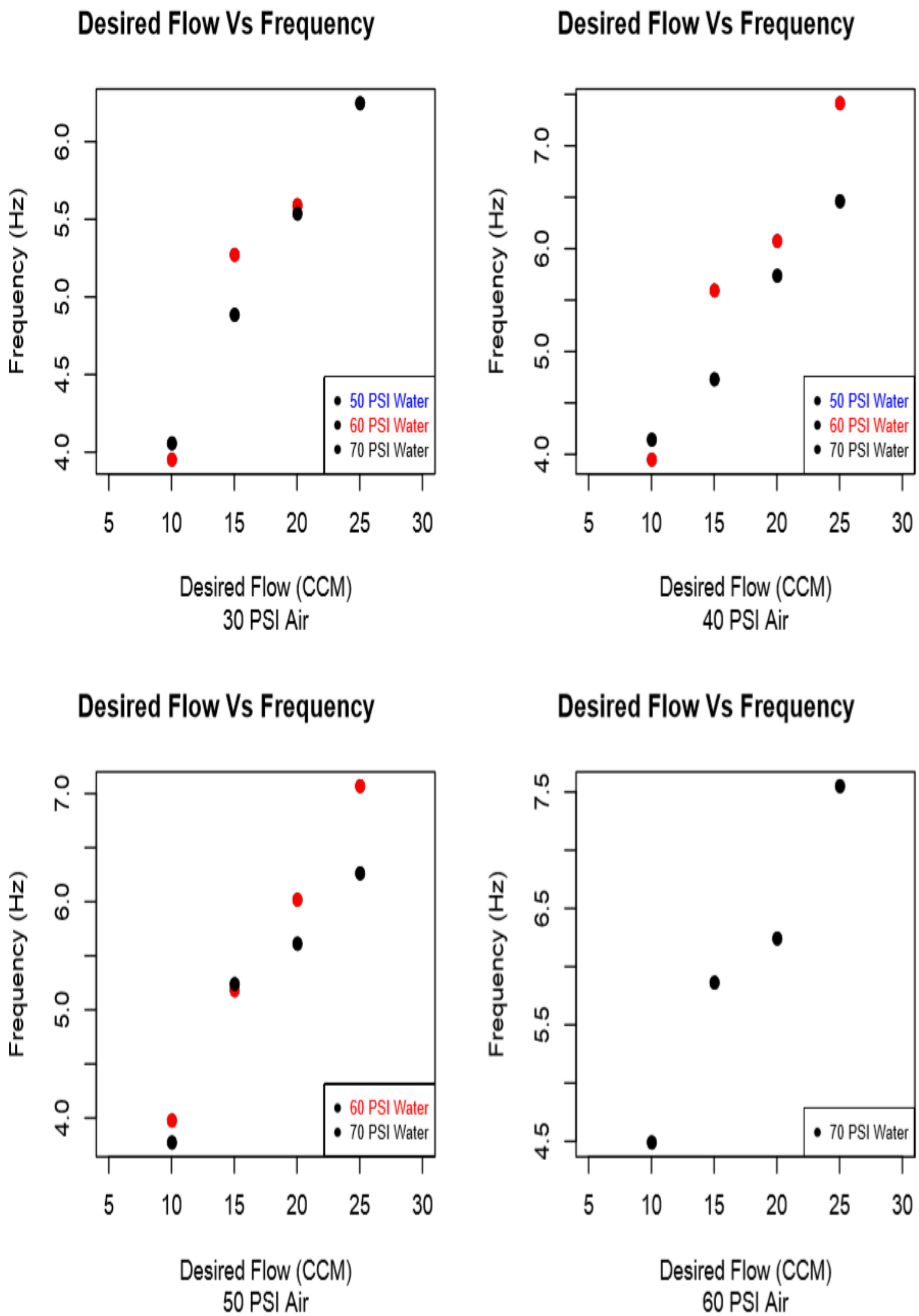


Figure 16: Frequency vs. water flow rate at different water and air pressure at the distance of 0.21 mm.

3.4.4 Frequency vs. water flow rate at different lengths

Since frequency was observed in very specific lengths, it was assumed that lengths might affect the result of atomization. Hence, frequency was plotted versus water flow rates at different lengths that could create pulses from the nozzle under the circumstance described in sections 3.4.1 and 3.4.2. Figure 17 to 19 depicts these lengths were 0.5, 0.4 and 0.3 mm. The results show a heightened water volume from frequencies by increasing the water flow rate and distance from counterflow surface.

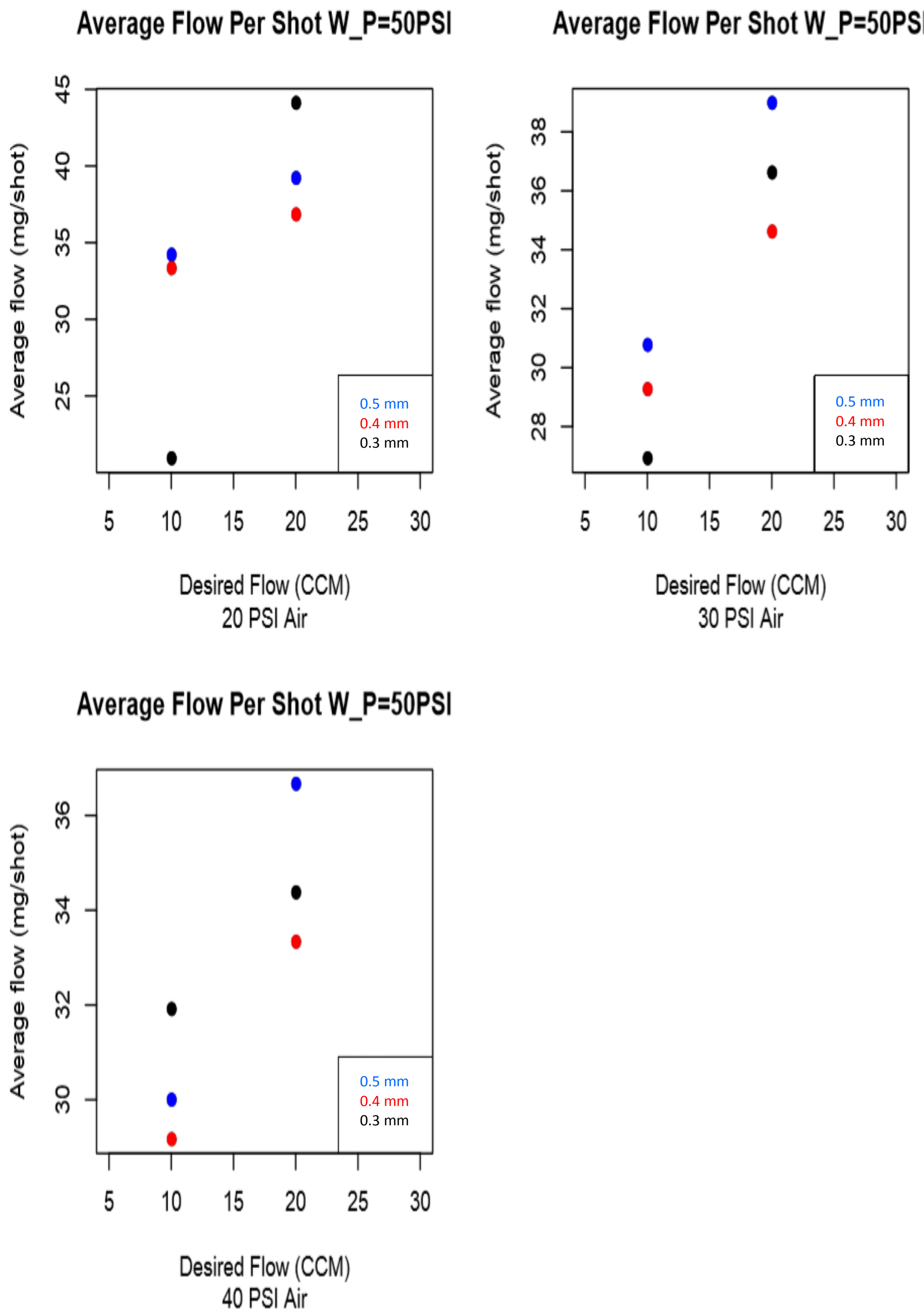


Figure 17: Frequency vs. water flow rate at different distances at water pressure of 50 psi.

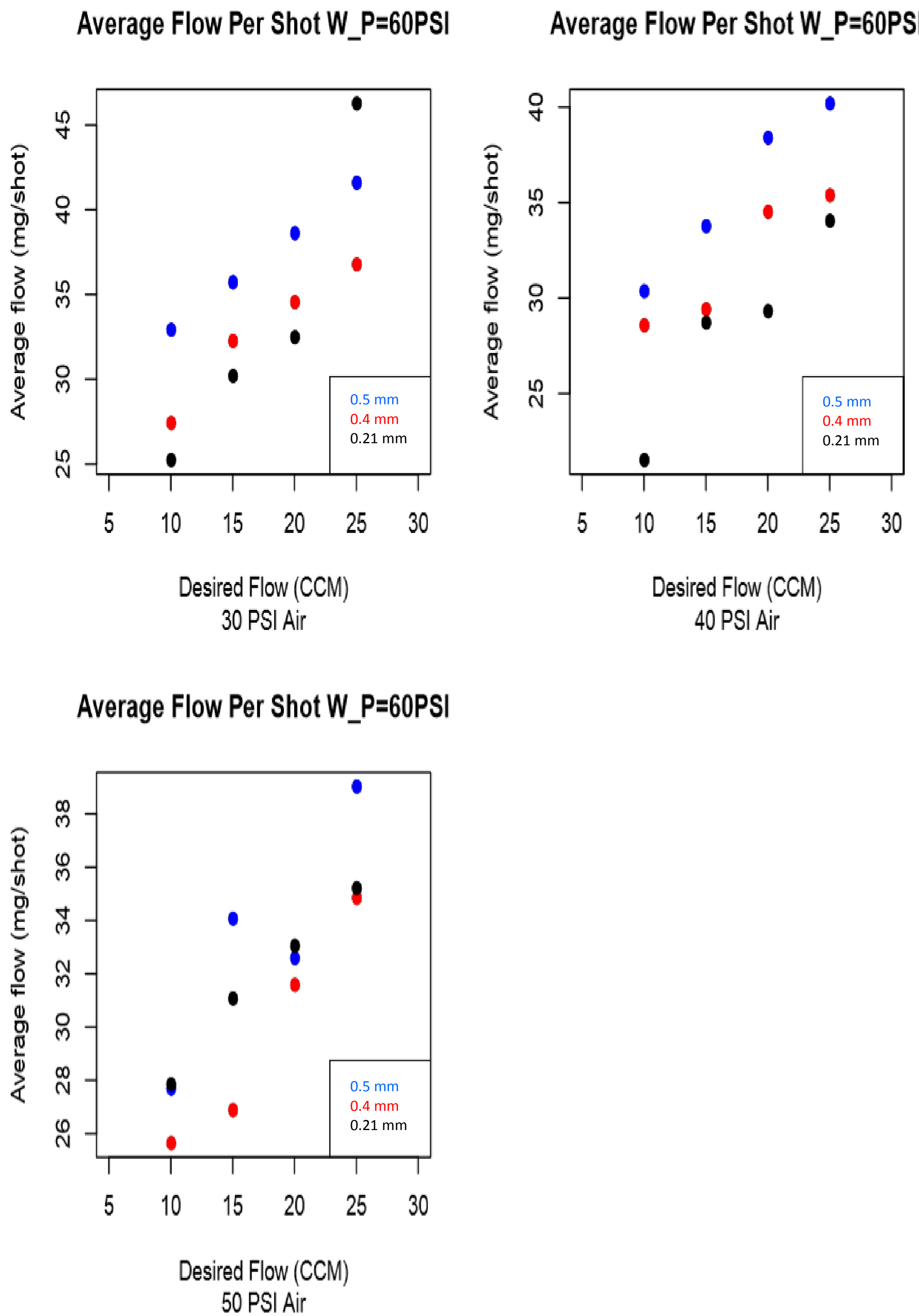


Figure 18: Frequency vs. water flow rate at different distances at water pressure of 60 psi.

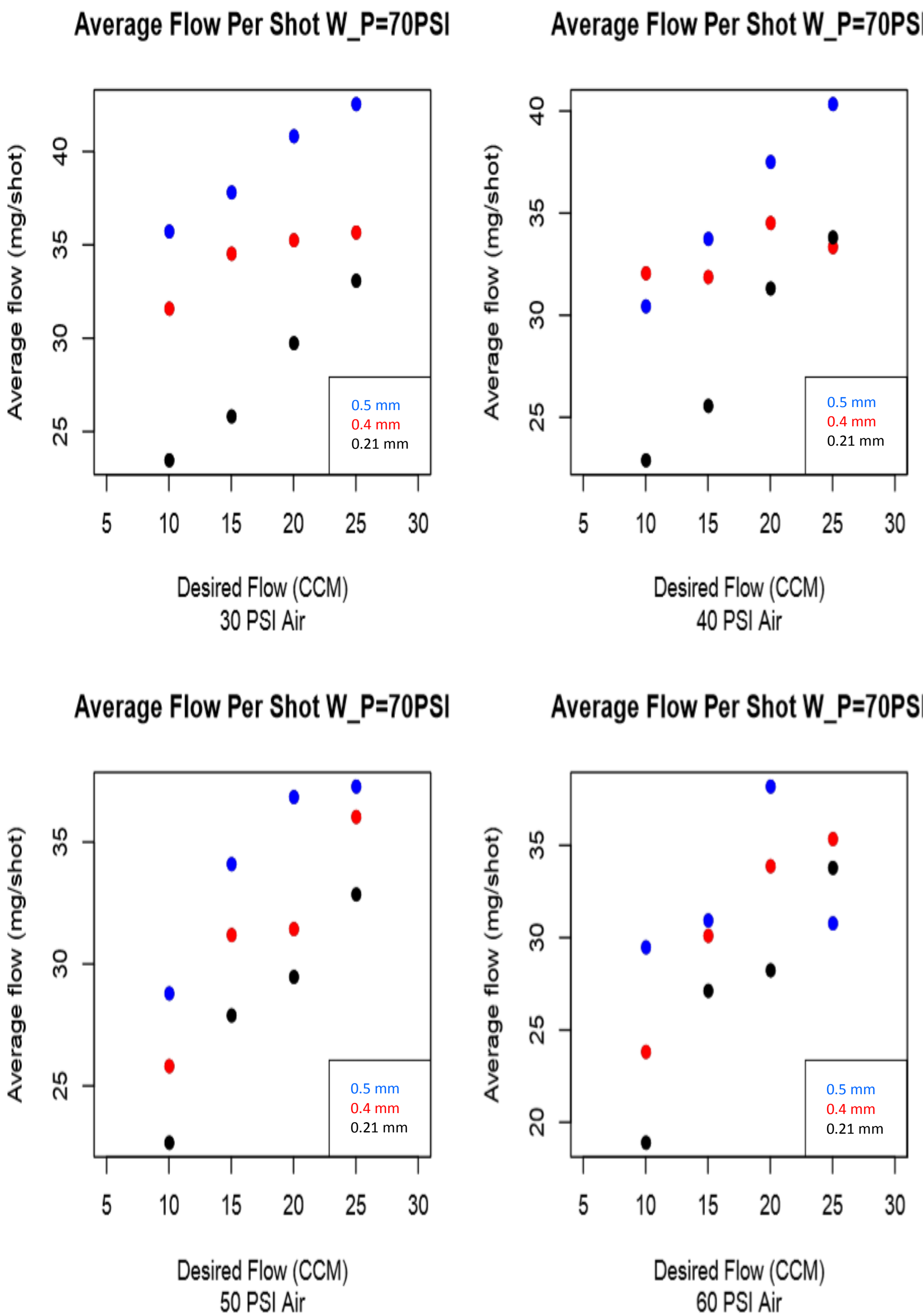


Figure 19: Frequency vs. water flow rate at different distances at water pressure of 50 psi.

3.4.5 Spray angle vs. water flow rate at different lengths

Even though angles of spray did not affect atomization, it was investigated here to check if there is any difference between angles at different frequencies. As shown in figure 20, angles were measured and plotted versus water flow rate at different lengths of 0.5, 0.4 and 0.21 mm When H was 0.21 the angle could not be measured because the spray was like a cloud and spray was not visible. The results also show that changing the pulsing mode did not significantly affect the angles.

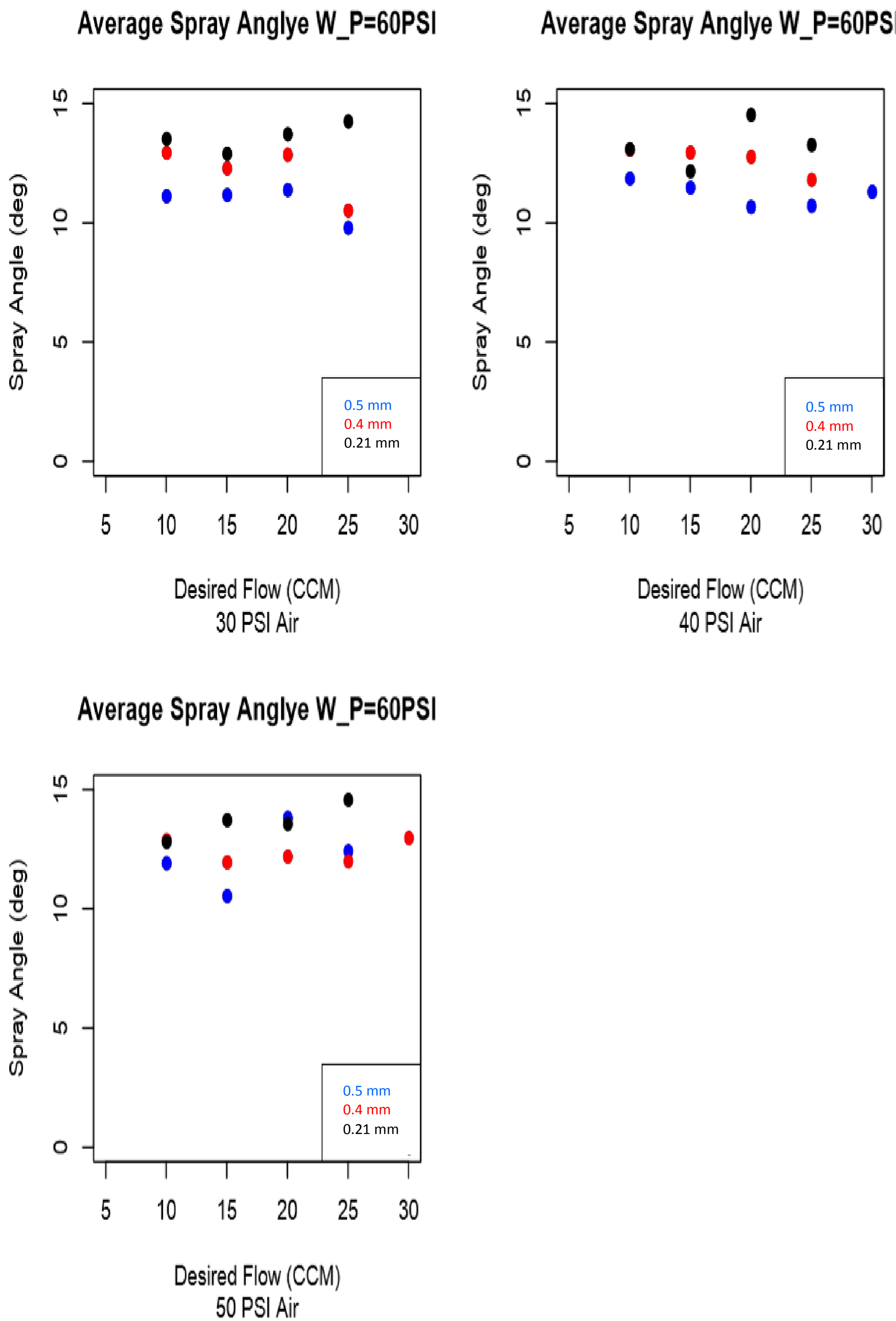


Figure 20: Angle vs. water flow rate at different distances

The water droplet size was measured using particle image velocimetry (PIV) laser at the optimal operating conditions that was achieved previously. As shown in figure 20, the results from the laser depicts that the droplet size is between 10 to 30 micrometer, which is desirable.

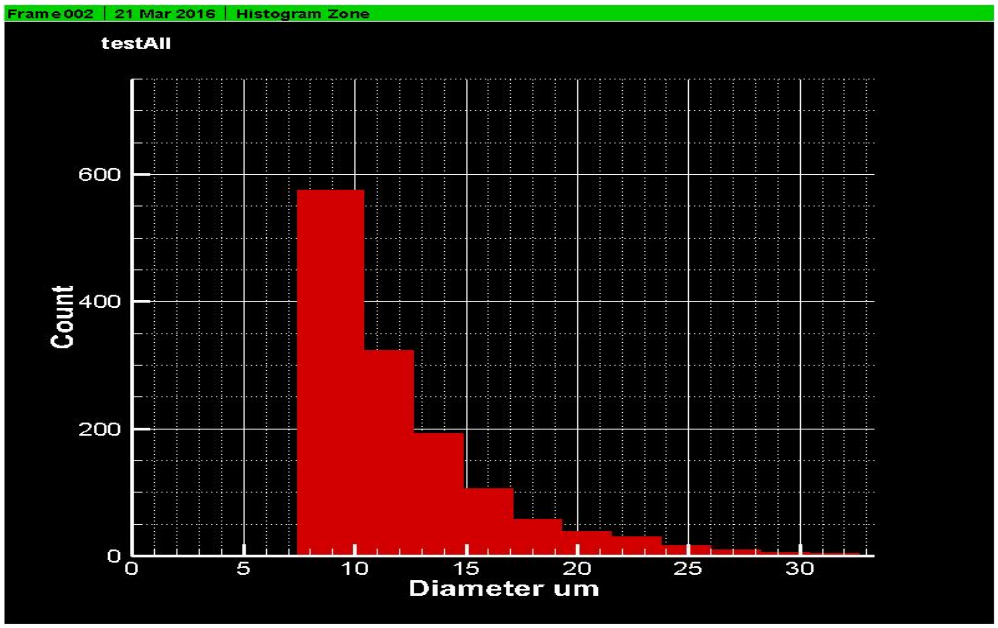


Figure 21: Droplet size measured using PIV laser.

3.5 Discussion

Results confirmed that the counterflowing atomizer can create spray with smaller droplets compared to previous atomizers. The measurements of Gañan-Calvo suggest that for an H/D ratio less than 0.25, the character of the flow undergoes a drastic change: the co-flowing outer fluid no longer goes downstream but penetrates into the nozzle, creates a reverse flow inside the nozzle [4]. In the case of the counterflowing nozzle, the flow condition observed in flow blurring occurs independent of H/D; therefore, an efficient atomization regime similar to flow blurring theory was observed.

Although it was concluded that the air pressure and water pressure affect the atomizer, these pressures do not need to be as high or low as those required by airblast or effervescent atomizers. This means a counterflowing nozzle can create a fine mist under achievable conditions.

While characterizing the operating modes of the nozzle, two different operating conditions achieved atomization: continues and pulse mode.

Subsequently, to have a fine spray with small droplets, the water tube should be kept at a distance of $0.5207 \text{ mm} < H < 1.5207 \text{ mm}$. The optimal result can be found at air pressures between 50 and 60 psi and similar water pressure. Since the water flow rate can affect the air flow rate at the highest level, the water flow rate should be held at 10 to 12 CCM and the air flow rate should be at the maximum possible that can be achieved at 50 psi.

Frequency strongly depends more on the water pressure and water flow rate than air pressure and air flow rate. It somewhat depends on the length and air pressure. In addition, spray angle is not very sensitive to water flow rate and air pressure.

These operating conditions corroborate and refine the results achieved from the flow blurring nozzle. It shows that the counterflowing nozzle can creates a fine mist with small droplets without requiring specific geometric conditions.

Future studies should focus on the velocity and the droplet size of the spray created by counterflowing nozzle at the achieved optimal conditions. Instruments such as flow meter and pressure gauge were used to characterize counterflowing nozzle using water and air as the two main fluids. These instruments can be improved for experimenting on soybean oil and diesel oils; for instance, the accuracy of equipment needs to be considered. More detail about applications, efficiencies, market, and future of the nozzle was explained in Chapter 4.

Chapter 4: Marketing Plan of Counterflowing Nozzle

4.1 Introduction

In this section, situation analysis and market strategies is done on the counterflowing nozzle. Therefore, potential customers, market trends, projected growth, competitors, and SWOT analysis of counterflowing nozzle will be investigated. Since the counterflowing nozzle is in its early stages, financial changes will be considered in future studies.

4.2 Situation analysis

A counterflowing nozzle is an atomizer that provides a spray with smaller droplets compared to other proposed atomizers discussed in the literature review. Dr. Hoxie patented the counterflowing nozzle about two years ago and it was characterized by Zahra Omidiannia. Characterization has been done to demonstrate how this nozzle can perform under different conditions and ascertain that it is ready to enter to the competitive market of atomizers. As it was explained before, atomization has received attention in industry for years.

4.2.1 Market summary

The goal of making counterflowing nozzle was to address the weaknesses of the previously made nozzles such as high cost. Ample information about previous atomizers explained in the literature review will contribute to finding customers and meeting their needs. Regarding the two modes of the counterflowing nozzle, its market includes companies that require spray with fine mist out of liquid with high and low viscosity and industries that require pulsing spray in their manufacturing processes. Thus, target markets are:

- Medical device manufacturers
- Paint sprayers manufacturer
- Agriculture
- Power generation

4.2.1.1 Market needs

Counterflowing nozzle is suitable for atomizing wide variety of liquids such as biofuels that have high viscosities. Counterflowing nozzle was designed to fulfill the following needs of customers:

- Simple design: counterflowing nozzle has a simple design like flow blurring nozzle, hence it can be easily manufactured and it is inexpensive.
- Efficiency: the price of biofuels is higher than other fossil oils. Therefore, industries require a high efficiency atomizer that creates a fine mist and uses less biofuels. The counterflowing nozzle is capable of making finer and more efficient spray. For instance, combustion will be done more efficiently if the spray be created by counter flowing nozzle in a combustion engine.
- Easy to use: this research considered the simplicity of use. The counterflowing nozzle can be used in different equipment and also doesn't require very specific geometric conditions for operation. It also doesn't require much maintenance.
- Feasible operation condition: counterflowing nozzle can perform efficiently under different conditions while it is independent of ALRs (air liquid ratios). Moreover, it doesn't require specific geometry condition and it still has higher and better performance in comparison with other nozzles. The life span of counterflowing nozzle is longer than other atomizers.

4.2.1.2 Market trends

As it was mentioned earlier in the literature review, the first atomizer was invented by Dr. Allen DeVilbiss in the 1800s for medical proposes [3]. Beside medical usage, atomizers can have different applications that make researchers and industries interested in this area, which resulted in more research. After the very first atomizer, airblast atomizer was made followed by effervescent atomizer in 1980 [12, 13] and then flow blurring in 2005[4].

Advances in the efficiency of burning alternative fuels in engines are actively being pursued to revolutionize systems in the transportation and industrial sectors. In 2013, 92% of the 26.9 quadrillion BTUs consumed for transportation came from petroleum, and just under 5% from biomass. In the industrial sector, 40% of the 21.5 quadrillion BTUs consumed was from petroleum and 10% from renewable resources. At these scales even small increases in engine efficiency have enormous impacts on emissions and the production of carbon dioxide [1]. According to a United States Department of Agriculture study, 60% of the energy required to produce biodiesel is attributed to the conversion process [2]. Improving atomization and combustion to the point that bio-oils can be used without damage to gas turbine engines will reduce energy consumption and cost.

Increases in the number of applications for atomization, increases demand. Thus, airblast atomizer and effervescent atomizers are being used in different equipment. Equipment that uses atomizers for both airblast and effervescent atomizers are combustion engines, nebulizers, aero engines, paint sprays, gas turbine, and diesel engines [19, 20], which means that the more efficient the atomizers work in these equipment the better performance they will have, because these types of equipment cannot work well without atomizers. However, the equipment is working under specific conditions which make their performance limited and also not many fuels can be used in them which increases demand and therefore the market.

Atomizers became more efficient through the years. However, the provided nozzle is an improvement to all other atomizers and can take their places because of its unique specifications, which increases the demand for counterflowing nozzle.

4.2.1.3 Market growth

The market for atomizers have been steadily increasing and one of the most important advantages of counterflowing nozzle is creating small droplets that will increase the combustion efficiency using both high and low viscosity liquids.

4.2.2 SWOT analysis

The following SWOT analysis lists the strengths, weaknesses, opportunities, and threats of the project.

4.2.2.1 Strengths

- High efficiency: in comparison to previously made atomizers, the counterflowing nozzle can create a better spray, which is uniform and make a mist with smaller droplets independent of (ALRs) as explained in methodology section.
- Simple design: the counterflowing nozzle design is very close to flow blurring nozzle. The only difference is the counterflow surface on the end cap that can be easily manufactured.
- Easy to use: it does not require very specific geometric conditions for use and it can be assembled and disassembled easily.

- Many applications: results of characterization of the counterflowing nozzle showed that it can be used for liquids with different viscosities, which increases the numbers of its industrial applications.

4.2.2.2 Weaknesses

- Counterflow surface is fragile: as shown in the methodology, the counterflow surface is very small, so caution is required for assembling the end cap to the cylinder.
- Additional studies required: while the counterflowing nozzle can perform well, more studies and experiment are required. For instance, linear stability analysis needs to be done to determine velocity profiles that are absolutely unstable.

4.2.2.3 Opportunities

- Growing demand for more efficient atomizers: more efficient atomization has the potential to improve combustion of bio-oils to the point that they could become a drop-in fuel. The results of this research will have a transformative impact on fuel economy, emissions and CO2 mitigation. This is critical because it reduces the overall energy and cost in biofuel refining. Cost is one of the largest inhibitors to widespread adoption, and embedded energy determines to a large extent whether or not bio-oils are in fact a benefit over petroleum fuels. Improved atomization and combustion of bio-oils will improve local economies by enabling locally sourced energy, decreasing soot production and the release of unburned hydrocarbons. In addition, engine durability and fuel economy will be improved. This transitional energy source has a shorter carbon life cycle and an overall lower negative impact on the environment as compared to petroleum fuels. Transitioning to sustainable energy technologies is a global endeavor, affecting everyone the world over. Because of its strengths customers will pay attention to the counterflowing nozzle.

- Increasing interest in environmentally friendly products: environmentally friendly products are in high demand. Data proved that small increases in engine efficiency have enormous impacts on emissions and the production of carbon dioxide [1]. The results of this project and further research on counterflowing nozzle will have a transformative impact on fuel economy, emissions and CO2 mitigation.
- Increased government interest in university research: as stated by Bercovitz and Feldman, transferring technology from universities can affect the economy positively [21]. Therefore, government is paying more attention for research done in universities, which will help all researchers including people who work on atomizers to focus more on the project rather than looking for sponsors. This will make the process of developing and making atomizers faster [22].

4.2.2.4 Threats

- Capital requirements: in order to use a newly patented product, a company needs to invest a lot of money and time in the research on the counterflowing nozzle.
- Government policies: lots of regulation and policies such as “Product Market Regulation” to start a business and introduce a new product to market, which takes lot of time and is expensive [23]. It doesn’t allow the counterflowing nozzle to enter the market at the scheduled time.
- Consumers may be unwilling to purchase a new atomizer: adopting devices that can use counterflowing nozzle and replacing previous nozzles with the proposed

atomizer requires money and time. Since people are not interested in change, they prefer to use previous methods [24].

- Competitors have superior access to the channel of distribution: previous atomization methods have been in use since they were invented in 1800s [see page 1,35], which were mentioned in the market trend and literature review. They have an established reputation and market, which helps them to sell and distribute their product easier (to learn more about competitors, please refer to section 4.2.3).

4.2.3 Competition

As previously discussed, other nozzles are effervescent, airblast and flow blurring. All of these atomizers have applications depending on their design and their performance, but counterflowing nozzle will compete with them in the following applications. Other atomizers are mostly used in combustion engines and gas turbines for producing power by combustion of fuels, furnaces which are used as heating systems and boilers [19, 25]. Flow blurring and airblast can be used in nebulizers, also.

There are companies that are using airblast and effervescent atomizers in their product. General Electric is one of the powerful competitors that makes gas turbines [26], [27], and the other company is Parker which uses airblast atomizer for its aerospace gas turbines [28]. Oubok is a company that uses airblast in its nebulizers, which has medical usage [29]. Examples of companies that use effervescent atomizers are NASA for making products such as Low NOx combustor [30] and Beijing Shenkebosi Thermal Energy Engineering Technology that makes high pressure effervescent atomization oil gun [31]. As it was discussed each of these atomizers has drawbacks which don’t get fixed by being applied to an equipment. This will also decrease the performance of that equipment. These drawbacks will be eliminated and atomization will be improved if manufacturers use the counterflowing nozzle.

However, it should be noted that since the counterflowing nozzle is in its early stages, more studies should be done in the future to determine which uses is the best. Even though the counterflowing nozzle has advantages, which were discussed in the conclusion of methodology, in future studies researchers need to work on what is the best possible way to add the nozzle to equipment in order to replace other atomizers and get the market from competitors.

4.2.4 Keys to success

The keys to success are continuing characterization of the nozzle using high viscosity oils such as soybean oil. Although results were found for water and the design promised a good performance, future experiments can prove the efficiency of the nozzle more. Implementing the keys to success improves the satisfaction of customers.

4.2.5 Critical Issues for researchers

As a new patent, counterflowing nozzle is still on its early stages. Below are critical issues:

- Lack of money: money is required to implement this technology. Funds will be used for different purposes: salary to the people who does the future experiments, buying equipment with higher accuracy, maintenance, buying fuel such as gasoline and soybean oil, and unpredicted costs. Thus, finding a sponsor is a key success.
- Lack of Time: in order to stay competitive, the patent needs to enter the market before any other atomizers that might be made by potential competitors. Atomization is a rapidly growing industry, therefore it should be introduced to the market soon. Hence, the project should be managed properly.

- Difficulty hiring a knowledgeable researcher: the person who continues the project should be interested and have background in this area. After finding a person, training is required which will take time and will increase the time that was planned for doing the project.
- Finding a sponsor: even though the counterflowing nozzle promises good performance and efficiency, there will be problems in finding a sponsor. It is always hard to transfer the technology from university to industry specially if an innovation is in early stages because it is risky for industries and they mostly prefer to spend money on ideas generated in their company.

4.3 Marketing Strategy

In this section, goals, strategies, and tactics to enter the market has been explained.

4.3.1 Mission

The mission is to improve atomization and to provide an efficient atomizer to the customers across the world.

4.3.2 Marketing Objectives

- Increase stakeholders: stakeholders can be any organization, or industry, which are interested in the product. Having more stakeholders will help to achieve success because they can help us through many different things such as supporting and helping us for producing the product in mass and introducing the product to the market.
- Steadily continue the goals of the project to satisfy customers: by marketing and communicating with customers, we will learn more about customers' needs and we can add their needs to the goals of project such as reducing CO_2 emissions and

increasing atomization efficiency which will help us to confidentially enter our product to the market without thinking of challenges that we might face such as competing with other companies.

- Target new customers: we should not focus just on existing products that are using atomizers. By marketing we might find products in companies that never had atomizers and our atomizer can increase their performance. In this way we can have more customers for our product and expand our market.
- Increase the sale: By using a good marketing strategy, we can increase our sales and gain more profit.

4.3.3 Financial Objectives

Since different things such as equipment maintenance and delay might happen during experiments, the only and most important objectives at this stage is to conserve funds received for this project.

4.3.4 Target markets

Medical device: a nebulizer is a device that directs medicines by atomization and creates a mist to the lungs [32]. Thus, counterflowing nozzle that makes finer mist compared to other atomizers can be used in this medical device.

Paint sprayers: in order to paint products such as cars, doors, and street walls a paint sprayer is used. In order to paint very well, paint sprayers should create a very consistent mist. As it was addressed before uniformity in the spray is a very important factor in atomization [6]. Counterflowing nozzle can provide a very uniform mist in both pulsing mode and normal mode, which makes it very good for both automatic and manual paint sprayers.

Agriculture: a counterflowing nozzle can be used in pesticides, insecticide, and herbicides spraying machine, because it can make uniform spray with small droplets. These machines are used to treat different types of plants and trees.

Power generation: combustion engines and gas turbines applications make atomization a very interesting topic for researchers and scientist. The counterflowing nozzle can create a fine spray from high viscosity fuels, so it can be used in both.

4.4 Marketing Tactics

The goal of this section is to explain strategies that are going to be used to market the counterflowing nozzle which helps to find a sponsor.

4.4.1 Product

The counterflowing atomizer is a patent invented by Dr. Hoxie. The atomizer will have a great market because of the advantages that it has in comparison to other atomizers. Therefore, it requires to be protected and by doing more experiments the protection should be expanded and continued. In addition, a good manager is needed for finishing the project on time.

4.4.2 Communications

The best way to introduce the counterflowing nozzle and finding sponsor is communication which can be done in following ways. First is publishing a conference paper that helps other universities to learn about the product. Second is introducing counterflowing nozzle and its application by posting it on the university website. Third is writing a paper about characterization of the counterflowing paper and publishing it, so the world can read about it and get familiar with the nozzle.

4.5 Controls

One of the goals of the marketing plan for counterflowing nozzle is to find a sponsor to finish the project on time. Few factors should be controlled in order to achieve the goal. The performance of employees to decrease errors and time wasting. The accuracy and performance of devices should be checked regularly, so everyone would be sure of the results taken from experiments.

4.5.1 Implementation

In order to keep satisfying the sponsor, milestones such as planning, designing, developing, and testing a product should be met. This section completely depends on the future experiments, but following factors is listed to identify milestones:

- Defining experiments that needs to be done
- Reporting what it has been done after doing experiments
- Analyzing the results of different experiments

4.5.2 Marketing Organization

Dr. Hoxie and her team with the help of University of Minnesota are responsible for marketing the counterflowing nozzle.

4.5.3 Contingency Planning

- Difficulties and Risks
    - Entry to the market while competitors have already taken the market: introducing counterflowing nozzle is hard when other competitors that were explained in section 4.2.3. already are using other atomizers in their products and trust is built between them and their customers.

- Transferring the patent from university to industries: Even though organizations are increasingly interested in taking ideas for research done in university, the challenges and problems still exist, such as whether the project can be successful in real world or not [33].

- Worst-Case risks

  - Estimated fund for doing the project is not enough: different things such as needing new equipment, or changing researchers might happen, which will increase the fund required for the project.
  - Project does not finish on time: training new researches, waiting for equipment, and all other un predicted event will increase the time estimated to finish the project.

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